UCRL-CONF-154962

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Introduction to the National Ignition Facility

E. I. Moses

January 5, 2004

Society of Photo-Optical Instrumentation Engineers
Photonics West, San Jose, California, January 24-29, 2004

Introduction to the National Ignition Facility

Edward I. Moses
Lawrence Livermore National Laboratory
P.O. Box 808 L-466
Livermore, CA 94551

ABSTRACT

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber with room for nearly 100 experimental diagnostics. NIF will be the world's largest and most energetic laser experimental system, providing a scientific center to study inertial confinement fusion and matter at extreme energy densities and pressures. NIF's energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. Other NIF experiments will study physical processes at temperatures approaching 10^8 K and 10^{11} bar, conditions that exist naturally only in the interior of stars, planets and in nuclear weapons. NIF has completed the first phases of its laser commissioning program. The first four beams of NIF have generated 106 kilojoules of infrared light and over 16 kJ at the third harmonic (351 nm). NIF's target experimental systems are being commissioned and experiments have begun. This paper provides a detailed look the NIF laser systems, laser and optical performance and results from recent laser commissioning shots, and plans for commissioning diagnostics for experiments on NIF.

Keywords: Solid State Laser, Neodymium Glass, Inertial Confinement Fusion

1. INTRODUCTION

The National Ignition Facility (NIF) under construction at the Lawrence Livermore National Laboratory (LLNL) will be a center to study inertial confinement fusion and the physics of extreme energy densities and pressures.[1-5] The building housing the laser system, shown in Figure 1, was completed in September 2001 and the construction of all 192 ultra-clean and precision aligned beam path enclosures was completed in September 2003. In late 2002 NIF began activating its first four laser beam lines and by July 2003 NIF had delivered world-record single laser energy performance in primary (1.06 micron infrared light), second, and third harmonic wavelengths. The first diagnostics capability has been installed and physics experiments have begun.

When completed in 2008, NIF will provide up to 192 energetic laser beams for inertial fusion and high energy density physics experiments. We are also exploring enhancements to NIF including multiple wavelength laser operation and short-pulse, high-power capability on some of NIF's laser beams using modifications to NIF's laser architecture.

Among the many challenges in designing and building NIF has been the design, engineering, construction, and commissioning of what is arguably the largest precision optical instrument ever built. Optics research, and laser science and engineering has taken place at NIF on a scale never before attempted. The optics and optical systems for NIF are the result of over thirty years of laser and optical materials research and development at national laboratories and in private industry throughout the world. On NIF there are more than 7500 large optics of 40 cm or greater transverse size including laser amplifier glass slabs, lenses, mirrors, polarizers, and crystals. An additional 26,000 smaller optical components are used in NIF. The total area of precision optical surfaces in NIF is nearly 4,000 square meters.[6]

NIF's laser systems are precisely aligned to better than 250 microns and point accuracy on NIF laser beams is 50 microradians. This precision placement had to be achieved over laser beam path lengths of 350 meters. In addition NIF's

Fig. 1. The National Ignition Facility at Lawrence Livermore National Laboratory.

beampath is required to be extremely clean to ensure that laser optics remain free of dust particles. Special robotic transport and handling systems are used for all of NIF's modular optical components, which are assembled into large phone-booth sized line-replaceable units or LRUs.

We have now installed the optics and mechanical utilities required to activate 4 of NIF's energetic laser beams. Over the past year we have carefully studied the performance of these laser beams and we have carried out over 180 system shots. In addition, approximately 30% of the 7,500 meter-scale optics required for NIF have been completed as of the end of November 2003. These optics have been fabricated to NIF's specifications utilizing deterministic processes that were developed as a result of our multi-year research program. After a brief description of NIF's laser systems we will present some quantitative results on laser performance. We will also discuss our plans for completing NIF along with possible enhancements to NIF's capabilities for experimental science.

2. A DESCRIPTION OF NIF

The NIF laser system is shown schematically in Figure 2. NIF consists of a number of sub-systems including amplifier power conditioning modules, the injection laser system consisting of the master oscillator and preamplifier modules, the main laser system along with its optical components, the switchyards, and the 10-meter target chamber and its target and diagnostic experimental systems. The entire laser system, switchyards, and target area is housed in an environmentally controlled building. An integrated computer control system is located in the core of the facility to monitor, align, and operate the more than 60,000 control points required for NIF's operation.[7] A large cleanroom facility, the Optics Assembly Building is located at one end of NIF for assembling and installing the precision optical and opto-mechanical components that make up the NIF laser system. On the opposite end of the facility the Diagnostics Building houses experimenters, experimenter data acquisition systems, and target preparation and storage areas.

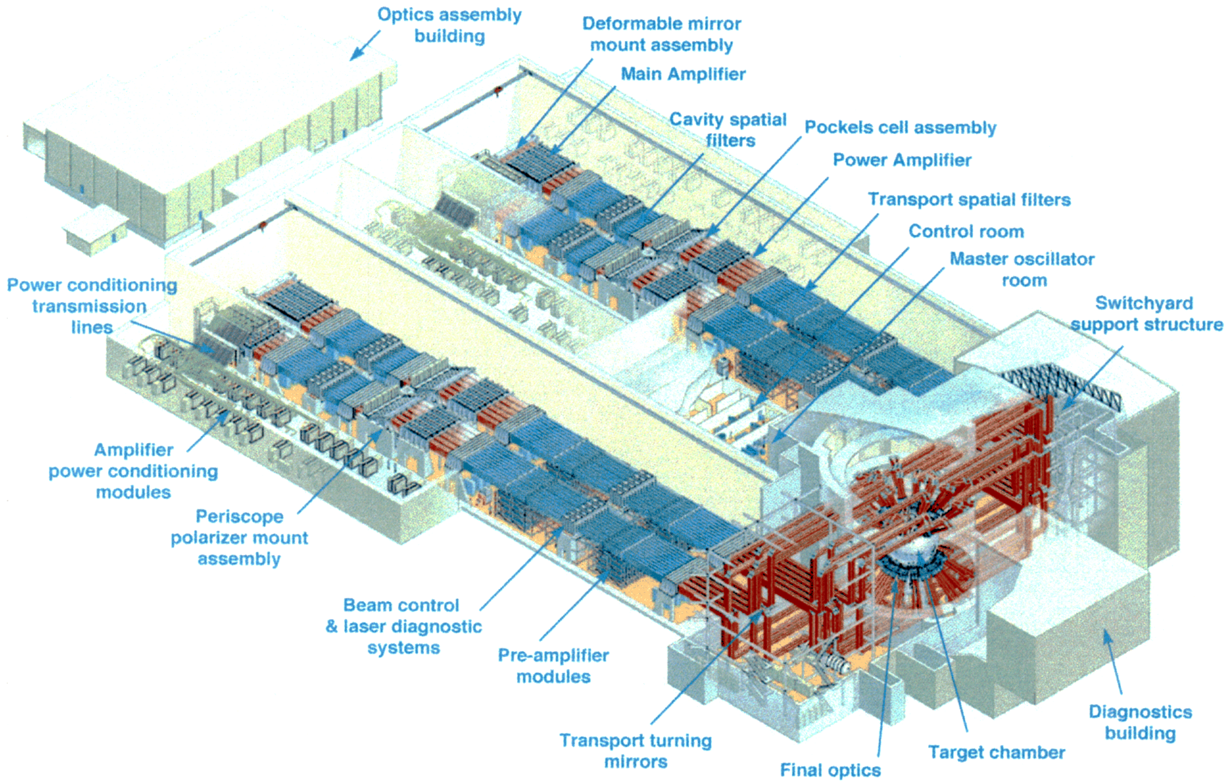

Fig. 2. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

NIF's laser system, the heart of the facility, is comprised of 192 high-energy laser beams. For inertial fusion studies these laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351 nanometer wavelength). This is approximately 60 times the energy available in the Nova laser, which was operated at LLNL between 1983 and 1999 and Omega Laser at the University of Rochester's Laboratory for Laser Energetics.

Figure 3 schematically shows one of the 192 laser beams, detailing the line-replaceable units that are used along the beam path. A NIF laser beam begins with a nanojoule energy laser pulse from the master oscillator and a diode-pumped fiber amplifier system that can provide a variety of pulse shapes suitable for a wide range of experiments, from complex high contrast pulses for ICF implosions to high-energy extended pulses. The master oscillator pulse is shaped in time and then transported to preamplifier modules (PAMs) for amplification and beam shaping. Each PAM first amplifies the pulse by a factor of one million (to about one millijoule) and then boosts the pulse once again by a factor of 20,000, this time to a maximum of 10 joules, by passing the beam four times through a flashlamp-pumped amplifier. There are a total of 48 PAMs on NIF, each feeding a "quad" of four laser beams. Figure 4 shows a photograph of NIF's Master Oscillator Room and Figure 5 show a NIF PAM.

From the PAM the laser beam next enters the main laser system, which consists of two large amplifier units – the power amplifier, and the multi-pass or main amplifier. These amplifier systems are designed to efficiently amplify the input pulse from the PAM to the mission-required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics. The amplifiers, with 16 glass slabs per beam, are arranged with 11 slabs in the main amplifier section and five slabs in the power amplifier section (the power amplifier can actually accommodate 7 slabs per beam if necessary for future applications). Together, even though of relatively low gain, these amplifiers provide 99.9% of NIF's power and energy. The amplifiers use 42 kilogram slabs, measuring 46 cm x 81 cm x 3.4 cm, of neodymium-doped

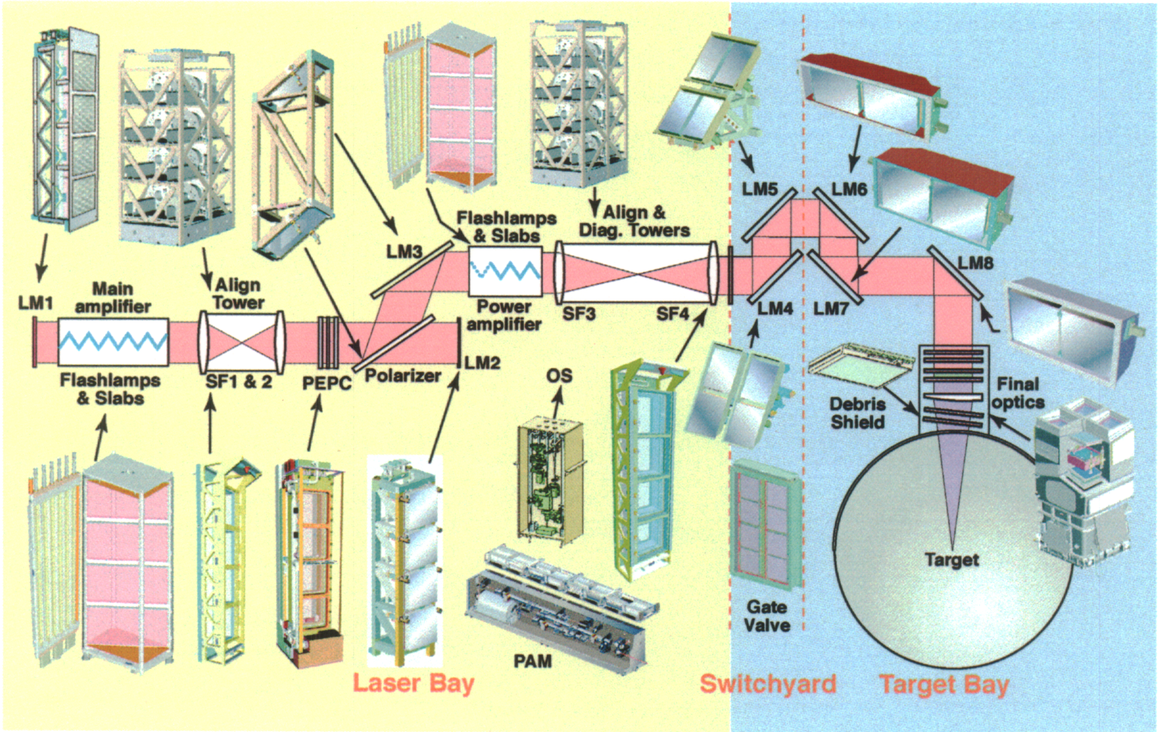

Fig. 3. Schematic representation of a NIF laser beam line showing the line-replaceable units used along the beam path.

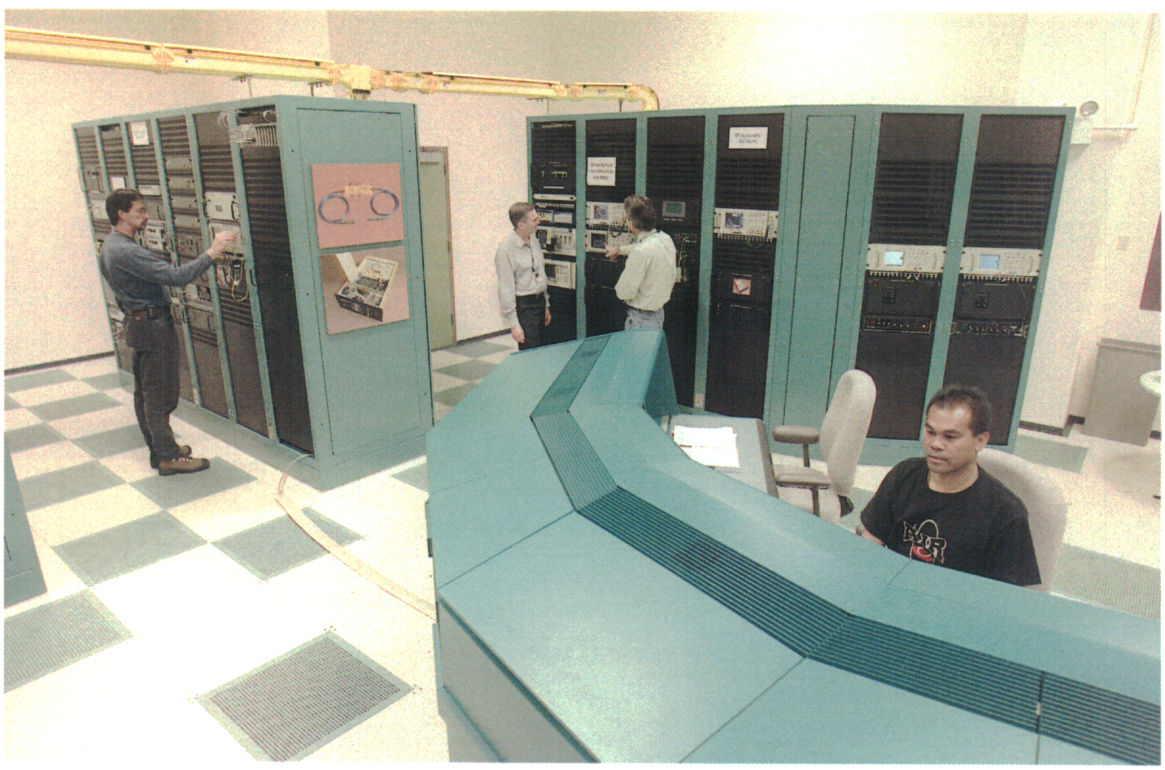

Fig. 4. The NIF Master Oscillator Room (MOR) has been operating continuously since October 2001.

Fig. 5. NIF Preamplifier Module (PAM) undergoing testing in the Preamplifier Module Maintenance Area, which is located adjacent to the MOR in a dedicated Class 100 clean room facility.

phosphate glass set vertically on edge at Brewster's angle to minimize reflective losses in the laser beam.[8-9] The slabs are stacked four high and two wide to accommodate a "bundle" of eight laser beams (see Fig. 6).

The slabs are surrounded by vertical arrays of flashlamps, measuring 180 cm in length. A total of 7680 flashlamps and 3072 glass slabs are required for NIF's 192 laser beams. Each flashlamp is driven by 30,000 joules of electrical energy from the Power Conditioning System (PCS), which consists of the highest energy array (about 400 megajoules) of electrical capacitors ever assembled.[10] The intense white light from the flashlamps excites the neodymium in the laser slabs to provide optical gain at the primary 1.06 micron infrared wavelength of the laser. Some of the energy stored in the neodymium is released when the laser beam passes through the slab. Advances in glass amplifier technology allow NIF to operate with less than twice the number of flashlamps than Nova even though the laser system will produce 60 times more output energy. The flashlamps are cooled between shots, along with the amplifier slabs, using nitrogen gas so that NIF can be fired once every four hours. Figure 6 shows how flashlamps and laser glass are assembled and installed into the NIF beampath.

A key component in the laser chain is an optical switch called a plasma-electrode Pockels cell (PEPC), which allows the beam to pass four times through the main amplifier cavity.[11] This device uses electrically induced changes in the refractive index of an electro-optic crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the PEPC allows light to pass through or reflect off the polarizer. The PEPC will essentially trap the laser light between two mirrors as it makes four one-way passes through the main amplifier system before being switched out to continue its way to the target chamber. The PEPC consists of thin KDP plates sandwiched between two gas-discharge plasmas that, although having no effect on the laser beam passing through the cell, serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently. Figure 7 shows a four-cell PEPC (optical switch) in operation that will be oriented vertically in a single unit when inserted into NIF's beampath.

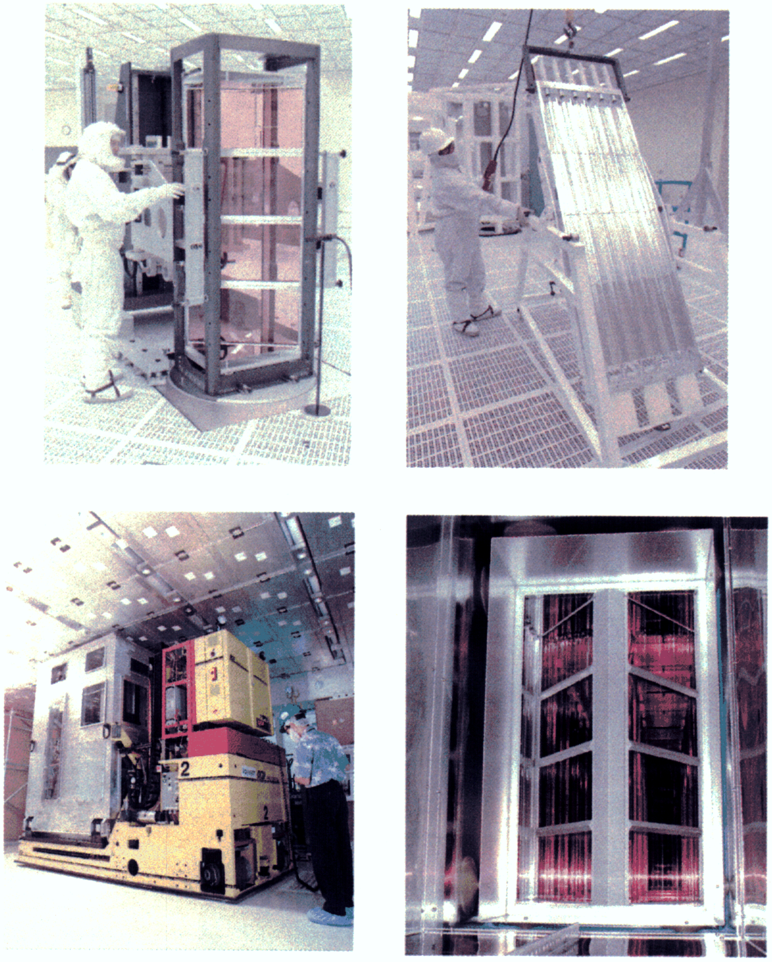

Fig. 6. Laser glass slab and flashlamp cassettes, shown in the top left and right photographs are examples of NIF LRUs. The LRUs are inserted into the laser beampath using autonomous guided vehicles carrying portable clean canisters, shown in the bottom left photograph. One section of the assembled amplifier system is shown in the bottom right photograph.

Fig. 7. Plasma Electrode Pockels Cell LRU undergoing testing in the OAB.

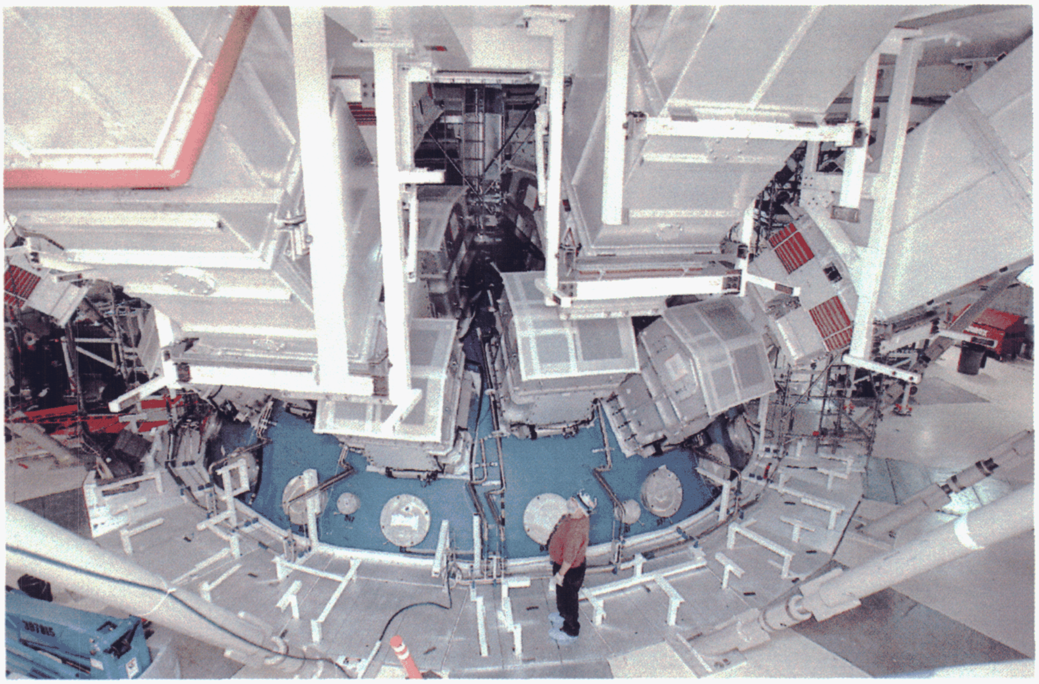

Fig. 8. Target chamber upper hemisphere showing 24 quads of beam tubes installed.

All major laser components are assembled in clean, pre-aligned modules called line-replaceable units or LRUs. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filter assemblies that are robotically installed into NIF's beampath infrastructure, while maintaining the high level of cleanliness required for proper laser operation. Autonomous guided vehicles carrying portable clean rooms position themselves underneath NIF's beampath enclosures and robotically insert LRUs into the beampath. The installation, integration, and commissioning of the beampath infrastructure at the required cleanliness levels has been successfully accomplished for the more than 120 LRUs required for NIF's first four laser beam lines.

The NIF target chamber and final focusing system is designed with maximum flexibility for experimental users and includes120 diagnostic instrumentation and target insertion ports. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating the fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to implode the capsule. NIF can also be configured into a more symmetrical "direct drive" arrangement of beams.[12] Figure 8 shows a recent photograph of the upper half of the target chamber. Each laser entry port allows a quad of laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing optics to provide a variety of beam profiles on target, KDP and deuterated KDP plates to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam.

3. NIF EARLY LIGHT

NIF construction began in May 1997 and nearly all192 beampath enclosures are now in place and ready for optics installation. Figure 9 shows the beampath installed in Laser Bay 2. In October 2001 the first laser light from NIF's master oscillator was generated in the master oscillator room located in the central core of the NIF building. This master oscillator has demonstrated the required pulse shaping stability and accuracy for high contrast ignition pulses and other types of laser pulses that are of interest to NIF experimenters. In June 2002 the first preamplifier module was installed in the Laser Bay and routinely amplifies master oscillator pulses to the joule level.

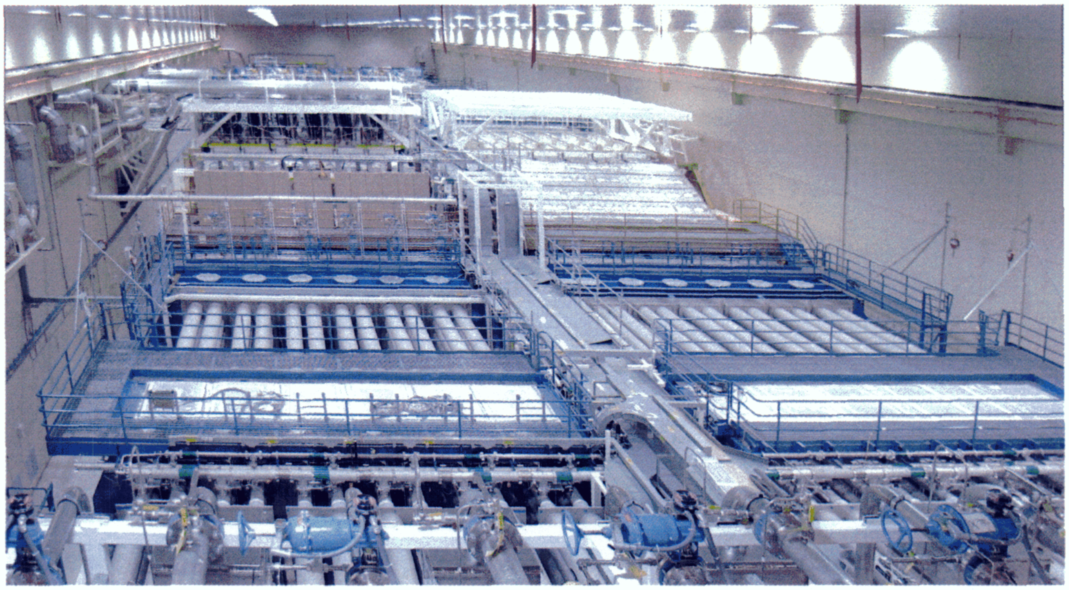

Fig. 9. The completed beampath for 96 laser beams in Laser Bay 2.

First high energy 3ω laser light to the center of NIF's target chamber was achieved in January 2003 with approximately 1 kilojoule (kJ) of laser energy focused onto a simple foil target. The energetic x-rays emitted from this target were measured with an x-ray pinhole imaging system called the Static X-ray Imager (SXI) mounted on the target chamber. In April 2003 10.6 kJ of 3ω light was produced in four beams and directed to a target in the target chamber. Recently we have delivered 16 kJ of 3ω light in four beams to the target chamber for experiments.[13]

A separate target chamber, known as the Precision Diagnostic System (PDS) is used to fully characterize NIF's 1ω, 2ω, and 3ω laser beam energy, power, and wavefront to validate and enhance computer models that predict laser performance. Any one of the four NIF beams can be directed into the PDS using a robotic mirror and transport system. Figure 10 shows examples of high-energy 2ω and 3ω beams imaged in the near field using the PDS.

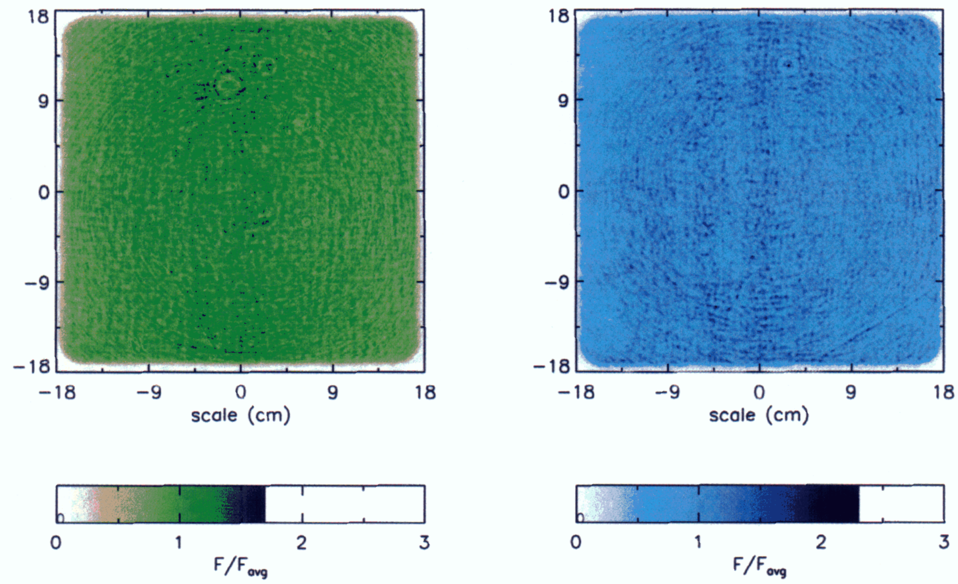

Fig. 10. Near field image of an 11.4 kJ 2ω and 10.4 kJ 3ω NIF beams showing excellent contrast uniformity, exceeding NIF's requirements.

At this time NIF's highest 3ω single laser beam energy is 10.4 kJ, equivalent to 2 MJ for a fully activated NIF, exceeding the NIF energy point design of 1.8 MJ. This energy was achieved with 13.65 kJ 1ω drive in a 3.5 ns pulse. We have also conducted a series of shots generating green or 2ω laser light with single beam energy up to 11.4 kJ in a 5 ns square pulse. This is equivalent to nearly 2.2 MJ on target for 192 beams. In July 2003, 26.5 kJ of 1ω light per beam was produced. This energy is 30% greater than the drive energy required for NIF. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world. High power campaigns have also been completed with drive power reaching 7 terawatts or about 5 gigawatts/cm2. Figure 11 details energy and power achieved on a number of 1ω shots conducted through July 2003.

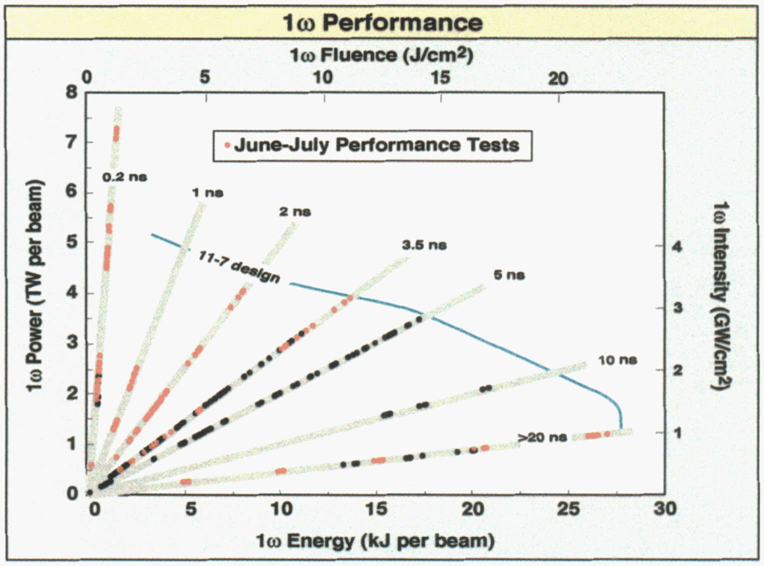

Fig. 11. 1ω energy vs. power is plotted for a number of NIF performance shots. The plot also indicates the level where energy and power is limited by the available number of glass slabs in the main amplifier (11 slabs) and the power amplifier (7 slabs).

Beam-to-beam synchronization has been measured and adjusted to better than 6 picoseconds, which corresponds to approximately 1 part in 150,000 of the total beampath in NIF. Figure 12 shows this measurement using an x-ray streak camera diagnostic demonstrating NIF's timing performance. Complex shaped ignition pulses as well as ramped and flat-in-time pulses with multi-kJ energies and pulse lengths up to 25 ns have also been demonstrated.

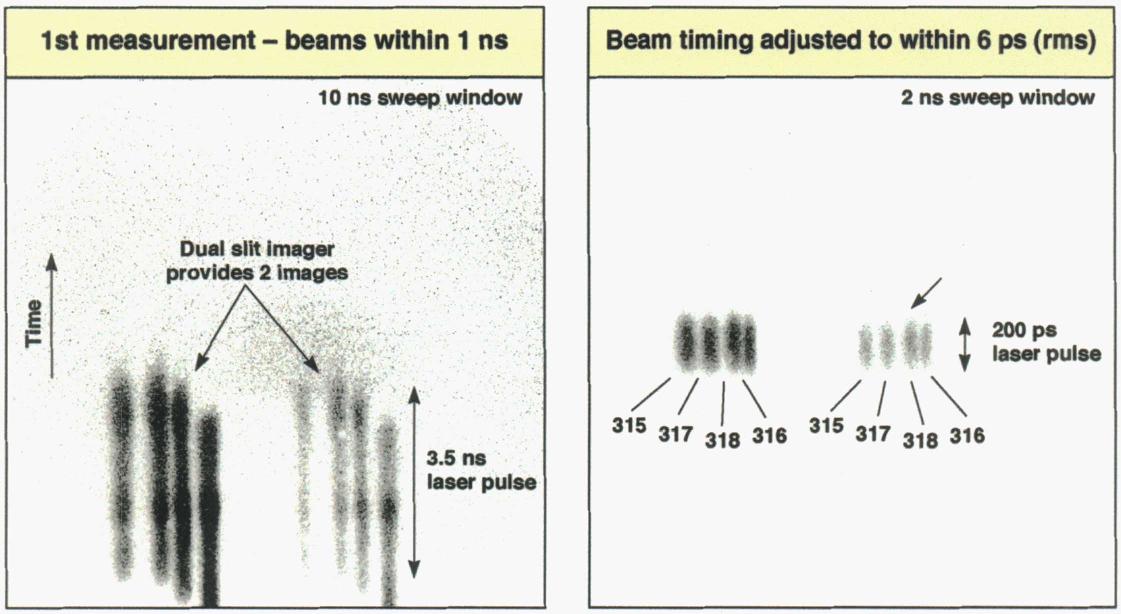

Fig. 12. Streaked x-ray images showing the beam-to-beam timing for a quad of four laser beams. Each image shows x-rays emitted from a target illuminated by the quad of beams and imaged through two different thickness filters.

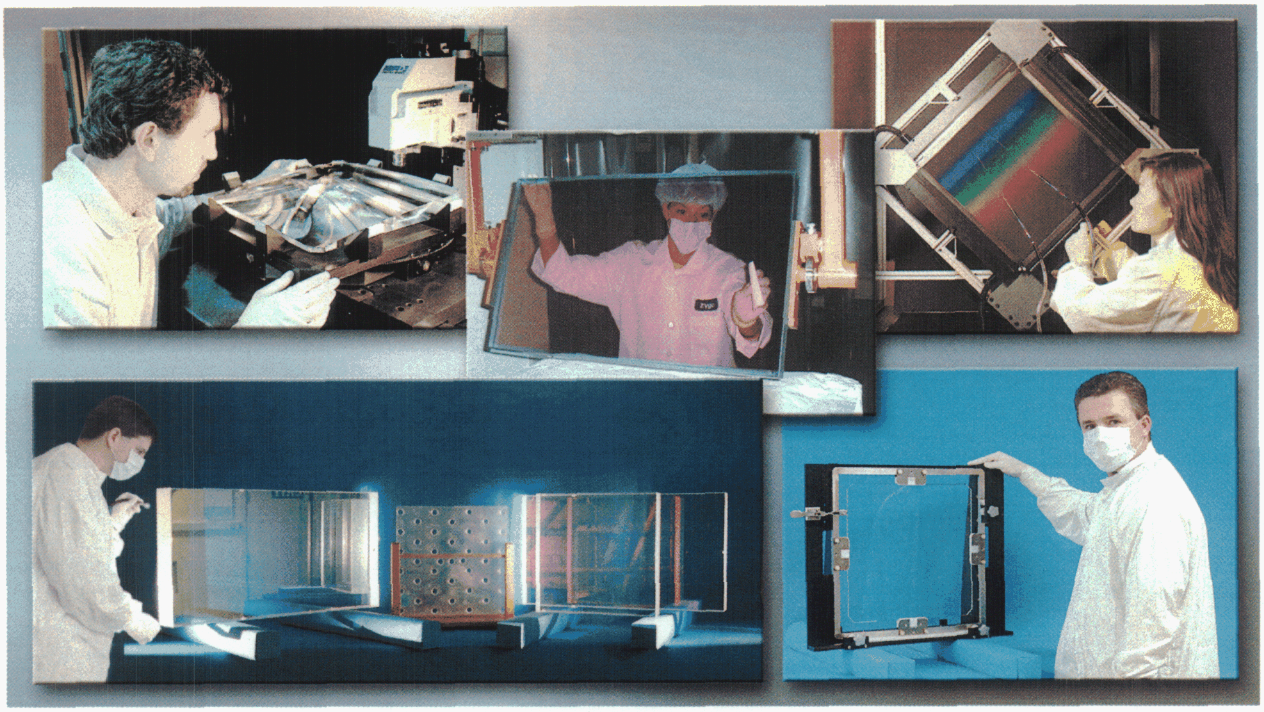

Fig. 13. Examples of large optics used on NIF. Clockwise from upper left: fused silica wedged focus lens, neodymium-doped phosphate laser glass slab, fused silica beam sampling grating, KDP frequency conversion crystal, and BK7 mirrors and polarizers.

4. NIF OPTICS

Optics production and finishing has been a major area of research over the past three years with an emphasis on making the finishing process more deterministic, reducing the iterative nature of traditional final figuring, and the optic preparation time (grinding and shaping) to prepare the optic for final figuring.[14-21] NIF vendors are now producing substantial numbers of optics that meet our requirements. A significant investment has been made in vendor facilitization programs, resulting in the installation of equipment based on new technology to meet the production capacity and metrology requirements for NIF.[6] Currently NIF's finishing vendors have finished approximately 30% of the optics required for NIF's 192 laser beams. NIF meter-scale optics suitable for high fluence operation with the required wavefront specification are being manufactured at a production rate of over 100 optics per month and we are following a schedule for completing production for all the necessary optics for 192 beam lines by 2007. Figure 13 shows some examples of the large aperture optics being used in NIF.

5. CONCLUSIONS AND FUTURE DIRECTIONS

The National Ignition Facility extends the experimental regimes of accessible high-energy-density (HED) by a significant amount compared to other current and planned high-energy laser and pulsed power facilities. NIF, and the French Laser Megajoule (LMJ) system (recently approved for construction) can drive materials to tens of gigabars for tens of nanoseconds. NIF is capable of providing a range pulse lengths that under certain configurations can be hundreds of nanoseconds. The ability to deliver extended high-energy drive allows experimental measurements of equation of state (EOS), materials at high pressures, hydrodynamics, and radiation transport that have not been possible in prior HED facilities.[22-23]

To facilitate the study of materials in HED experiments, we have begun the design and deployment of high energy petawatt (HEPW) beam lines on NIF. HEPW beams can provide advanced radiographic capabilities through the generation of energetic x-rays, protons, and electrons from the interaction of these intense laser beams with matter. NIF's baseline injection laser, main amplifier, and beam transport system can be modified to allow up to 20 high energy petawatt-class (HEPW) beams to be directed to target chamber center. Our initial plans are to install a single kilojoule-class HEPW beam line with 1-30 picosecond pulse width to drive electron or proton cone-focused ignition experiments. NIF long pulse beams totaling 250 kJ into an ignition target with 8-fold, 2-cone symmetry (8 quads of 4 beams in opposite laser entrance holes) would be used to compress the fusion capsule. This capability on NIF could be in place in 2006. Additional HEPW beams in a quad could be installed to provide multi-kilojoule capability in following years.[24]

Beam deployment on NIF supports experiments with steadily increasing capability, shown in Figure 14. The increasing symmetry and energy available enables a variety of target configurations including planar targets, horizontal and vertical half-hohlraums (halfraums), and vertical hohlraums with 4- and 8-fold symmetry that provides approximately 300 shots per year through 2008 for high-energy-density physics, inertial confinement fusion, and basic science. After project completion in 2008, NIF is expected to provide 700 shots per year as a national user facility. The first physics experiments are already being performed on NIF. Initial experiments are studying laser-plasma interactions and hydrodynamics of shocked materials. In the coming years this unique facility will already be providing the first glimpses of conditions heretofore only found in the most extreme environments. This will be done under repeatable and well-characterized laboratory conditions for the benefit of basic and applied science.

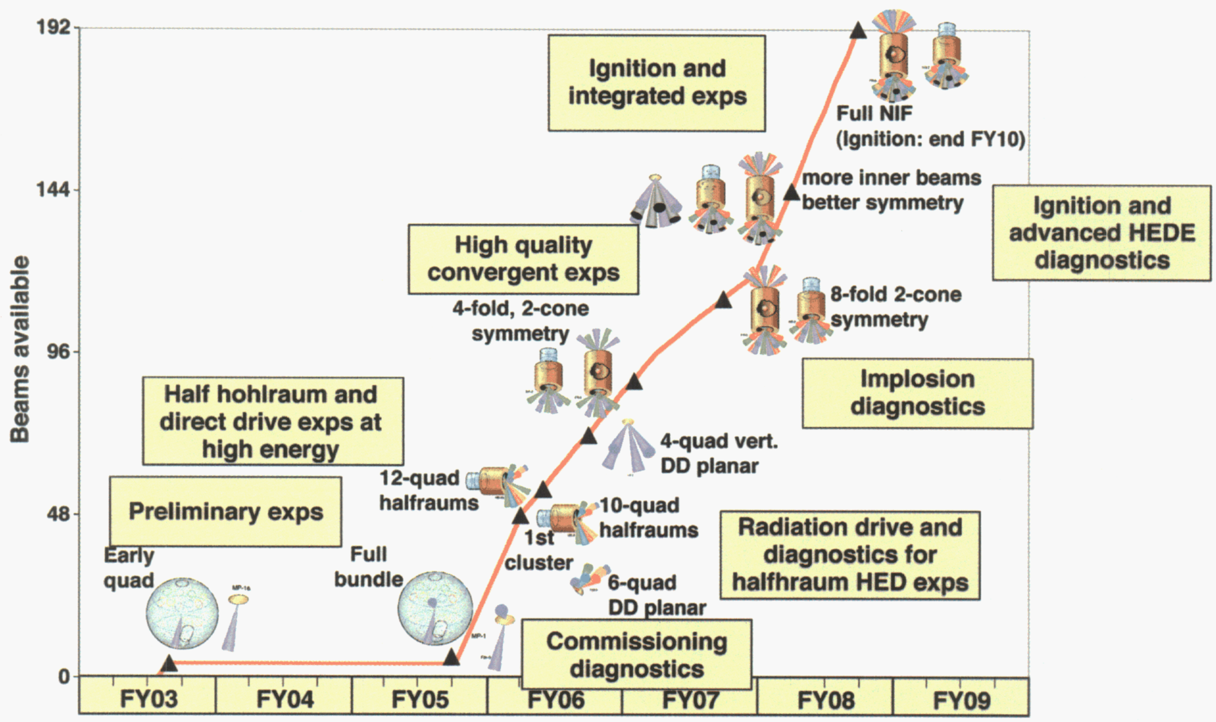

Fig. 14. The plan for completion of NIF provides increasing experimental capability over time for both experimental configurations and specialized diagnostics as more beams and symmetries become available.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to the many people, institutions, and industrial partners that are diligently working to build the National Ignition Facility.[25] This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

REFERENCES

1. J. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive,* Springer-Verlag (1998).
2. "Laboratory Microfusion Capability Phase-II Study," prepared by Interscience, Inc. for the Inertial Fusion Division Office of Research and Advanced Technology, ISI-TM9005281, May 31, 1990.
3. "Solid State Lasers for Application to Inertial Confinement Fusion," W. F. Krupke, ed., Proc. SPIE 2633 (1995).
4. C. B. Tarter, "Inertial Fusion and Higher Energy Density Science in the United States," Proc. 2001 Conf. On Inertial Fusion Science and Applications, K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier (2002).
5. E. Moses, et al., "The National Ignition Facility: Status and Plans for Laser Fusion and High-Energy-Density Experimental Studies," Fusion Science and Technology, V. 43, p. 420, May 2003.
6. E. Moses, et al., "The National Ignition Facility: The World's Largest Optics and Laser System," UCRL-JC-151593, SPIE Proc. 2003 Photonics West, January 2003.
7. P. Van Arsdall, et al., "The National Ignition Facility: Status of the Integrated Computer Control System," UCRL-JC-152832, submitted to the Proceedings of the International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS), Gyeongju, Korea, October 2003.
8. J. Campbell, et al., "Continuous melting of phosphate laser glasses," J. Non-Crystalline Solids **263&264** (2000).
9. J. Campbell and T. Suratwala., "Nd-doped phosphate glasses for high-energy/high-peak-powerlasers," J. Non-Crystalline Solids **263&264** (2000).
10. M. Newton et al., "Initial Activation and Operation of the Power Conditioning System for the National Ignition Facility," Proceedings of the International Pulsed Power Conference 2003, Dallas, TX, June 15-18, 2003.
11. C. Boley and M. Rhodes, "Modeling of Plasma Behavior in a Plasma Electrode Pockels Cell," IEEE Trans. Plasma Sci., **Vol. 27, No. 3**, June 1999.
12. S. Haan, et al., "Update On Target Design for the National Ignition Facility," Proc. 2001 Conf. On Inertial Fusion Science and Applications (IFSA 2001), K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier (2002).
13. S. Glenzer, et al., "Progress in Long Scale Length Laser Plasma Interactions," UCRL-CONF-155301, to be published in the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September (2003).
14. T. Parham, et al., "Developing optics finishing technologies for the National Ignition Facility", Inertial Confinement Fusion Quarterly Report, Lawrence Livermore National Laboratory, UCRL-JC-129317, 177-191(1999).
15. D. Aikens, et al., "Developing Enabling Optics Finishing Technologies for the National Ignition Facility," Lawrence Livermore National Laboratory, Livermore, CA UCRL-JC-129317, (1998).
16. P. Baisden, "National Ignition Facility (NIF) program update," Lawrence Livermore National Laboratory, Livermore, CA UCRL-JC-137357, (2000).
17. J. Lawson, et al., "Surface figure and roughness tolerances for NIF optics and the interpretation of the gradient, P-V wavefront, and RMS specifications," in Optical Manufacturing and Testing III, H. Philip Stahl, Editor, Proceedings of SPIE Vol. 3782, 510-517 (1999).
18. B. Stuart, et al., "Laser-induced damage in dielectrics with nanosecond to sub-picosecond pulses," Phys. Rev. Lett., **74**, p. 2248-51 (1995).
19. J. Menapace, et al., "Combined advanced finishing and UV laser conditioning for producing UV-damage-resistant fused silica optics," SPIE Proceedings, Vol. 4679, p. 56-69 (2002).
20. R. Brusasco, et al., "Localized CO_2 laser treatment for mitigation of 351-nm damage growth on fused silica," SPIE Proceedings, Vol. 4679, p. 40-47 (2002).
21. C. Stolz, et al., "Fabrication of meter-scale laser resistant mirrors for the National Ignition Facility, a fusion laser," submitted to the SPIE Proceedings of the International Symposium on Optical Science and Technology, Advances in Mirror Technology for X-ray, EUV Lithography, Laser, and Other Applications, 2003.
22. B. Remington, "High Energy Density Astrophysics in the Laboratory," Proc. 2001 Conf. On Inertial Fusion Science and Applications (IFSA 2001), K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier (2002).
23. "High-Energy-Density Physics Study Report," prepared by the National Nuclear Security Administration Office of Defense Programs, April 6, 2001.
24. C. Barty, et al., "Technical Challenges and Motivations for High Energy Petawatt Lasers on NIF," submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September (2003).
25. For more information on the National Ignition Facility, please visit our web site at http://www.llnl.gov/nif.